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Timing and patterns of debris flow deposition on Shepherd and Symmes creek fans, Owens Valley, California, deduced from cosmogenic ^{10}Be

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[1] Debris flow fans on the western side of Owens Valley, California, show differences in their depths of fan head incision and thus preserve significantly different surface records of sedimentation over glacial-interglacial cycles. We mapped fan lobes on two fans (Symmes and Shepherd creeks) on the basis of the geometry of the deposits using field observations and high-resolution airborne laser swath mapping data and established an absolute fan lobe chronology by using cosmogenic radionuclide exposure dating of large debris flow boulders. While both fans and their associated catchments were subject to similar tectonic and base level conditions, the Shepherd Creek catchment was significantly glaciated while that of Symmes Creek experienced only minor glaciation. Differences in the depth of fan head incision have led to cosmogenic surface age chronologies that differ in the length of the preserved depositional records. Symmes Creek fan preserves evidence of exclusively Holocene deposition with cosmogenic ^{10}Be ages ranging from 8 to 3 ka. In contrast, the Shepherd Creek fan surface was formed by late Pleistocene and Holocene debris flow activity, with major deposition between 86–74, 33–15, and 11–3 ka. These age constraints on the depositional timing in Owens Valley show that debris flow deposition in Owens Valley occurred during both glacial and interglacial periods but may have been enhanced during marine isotope stages 4 and 2. The striking differences in the surface record of debris flow deposition on adjacent fans have implications for the use of fan surfaces as paleoenvironmental recorders and for the preservation of debris flow deposits in the stratigraphic record.

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1. Introduction

[2] Numerous studies in the western United States, based on relative and absolute age constraints, have shown that long-term spatial variations in fan deposition are recorded by the presence of multiple depositional lobes, each of which was presumably active at a different time [e.g., *Denny*, 1965; *Hunt and Mabey*, 1966; *Hooke*, 1967; *Wells et al.*, 1987; *Blair and McPherson*, 1994; *Bierman et al.*, 1995; *Ritter et al.*, 1995, 2000; *Reheis et al.*, 1996; *Harvey et al.*, 1999; *Zehfuss et al.*, 2001]. The preservation of fan lobes is often limited by the inherent transience of fan surfaces because of both aggradation and burial of older deposits and to abandonment of active fan depositional lobes. This transience depends upon a variety of factors, both external (precipitation, catchment rock uplift, and basin subsidence) and internal (sediment production and mobilization, catchment sediment storage, and fan head incision).

[3] The presence of fan head incision, which is a widely observed phenomenon on arid region fans in the western United States [e.g., *Eckis*, 1928; *Bull*, 1964a; *Hooke*, 1967; *Bull*, 1977; *Harvey*, 1984], is particularly important for the preservation of multiple depositional lobes. While an incised fan head leads to abandonment of a former active fan lobe and a basinward shift of the depocenter, the absence of fan head incision causes proximal distribution of sediment and a resurfacing of the entire fan surface. Thus incision would cause the preservation of multiple depositional lobes, whereas a lack of fan head incision would result in a single depositional fan surface. The timescales over which lobes are active and abandoned, and the timing of fan head

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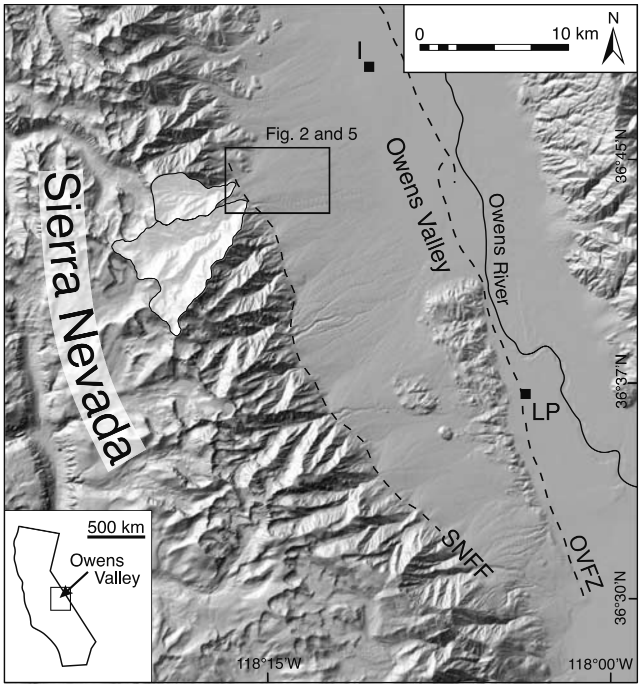

Figure 1. Shaded-relief map of our study location showing the Sierra Nevada and Owens Valley, California. Topographic data are based on U.S. Geological Survey 10 m national elevation data. Drainages of Shepherd and Symmes creek fans are outlined in white. The black box indicates the location of Figures 2 and 5. OVFZ, Owens Valley Fault Zone; SNFF, Sierra Nevada frontal fault; I, Independence; LP, Lone Pine.

incision itself, remain contentious and poorly understood, leading to competing models of fan development in the face of climatic and tectonic variations [e.g., *Lustig*, 1965; *Bull*, 1964b, 1991; *Hooke*, 1972; *Fraser and DeCelles*, 1992; *Hooke and Dorn*, 1992; *Whipple and Trayler*, 1996; *Allen and Densmore*, 2000; *Densmore et al.*, 2007]. Exposure dating of fan lobes with cosmogenic ^{10}Be now allows us to place absolute constraints on these timescales, enabling us to evaluate potential controls on fan incision mechanisms. In addition, given that deposition on fans is likely dependent on climate-modulated variations in sediment production and supply, absolute ages from exposure dating allow us to understand the resolution of fan surfaces as proxies for such external environmental variables [e.g., *Nichols and Fisher*, 2007].

[4] Debris flow fans on the western side of Owens Valley record sediment supply from catchments in the eastern Sierra Nevada, California, and show significant differences in their depths of fan head incision. Available absolute ages on fan deposition in the eastern Sierra come largely from fans with incised heads, such as the Lone Pine [*Bierman et al.*, 1995] and Fish Springs [*Zehfuss et al.*, 2001] fans. Deposition on Lone Pine fan occurred mainly between 140–100, 32–20, 14–10, and in the last 2 ka [*Bierman et al.*, 1995], and between 135–100, 34–22, 18–13 ka, and during the entire Holocene period on the Fish Springs fan [*Zehfuss et al.*, 2001]. Both data sets provide an important temporal framework on debris flow activity on Owens Valley fans, and demonstrate how incision is responsible for the preservation of a long-term record of debris flow activity, but do not allow us to gauge along-strike variations in fan depositional pattern, or the effects of catchment characteristics and fan head incision on the fan surface record.

[5] In order to investigate how the presence or absence of fan head incision controls the spatial patterns and timing of debris flow deposition, we chose two adjacent debris flow fans in Owens Valley, Shepherd and Symmes creek fans. The head of the Shepherd Creek fan is deeply incised, while there is nearly no incision at the Symmes Creek fan head. We expect that the spatial pattern of debris flow deposition on Shepherd Creek fan should be similar to Lone Pine and Fish Springs fans with multiple lobes of different ages. In contrast, the pattern on Symmes Creek fan should be relatively simple, with fewer lobes and a shorter depositional record.

[6] The goals of this paper are (1) to place absolute age constraints on the timing of deposition on debris flow fans in the eastern Sierra Nevada, (2) to compare the absolute depositional chronology with regional climate records, and (3) to evaluate the effects of fan head incision on the pattern of surface deposition. We also consider the implications of these depositional chronologies for understanding paleoenvironmental conditions and for the preservation of debris flow fan facies in the stratigraphic record. The mechanisms responsible for fan head incision in this setting are beyond the scope of this paper and are treated by *Dühnforth* [2007, chapter 4].

2. Setting

[7] Symmes and Shepherd creek fans are situated on the western side of Owens Valley, California (Figures 1 and 2). This area is tectonically dominated by dextral strike slip on the Owens Valley Fault, east of the fan toes [*Beanland and Clark*, 1994], and normal slip on the Sierra Nevada frontal fault [*Gillespie*, 1982], which offsets the fan heads (Figure 1). Late Quaternary normal-slip rates of ~0.2 mm yr^{-1} on the Sierra Nevada frontal fault were documented by *Gillespie* [1982]. The fans have surface areas of ~20 km^2 (Symmes) and ~30 km^2 (Shepherd). Surface elevations rise from ~1200 m above sea level at the distal part of the fans, to about 1875 m (Shepherd) and 1850 m (Symmes) at the fan heads. The head of Shepherd Creek fan is incised by about 45 m, whereas incision of Symmes Creek fan head is less than 5 m (Figure 3). Transport of sediment to Symmes and Shepherd creek fans and deposition on the fan surface is mainly accomplished by debris flows derived from their respective catchments. The fan surfaces are composed of abundant, crosscutting debris flow deposits with well-preserved debris flow channels, levees, and snouts [*Whipple and Dunne*, 1992] (Figure 4). Fluvial deposits on the fan surfaces are scarce and only occur in the active channel and in some reworked former debris flow channels. Both catchments and fans respond to local base level set by the Owens River.

[8] The watershed area of Symmes Creek is 12 km^2 compared with 36 km^2 for the Shepherd Creek catchment. The maximum catchment relief, defined as the difference between the elevation of the catchment mouth and the highest elevation of the ridge crest, is 2540 m for Shepherd

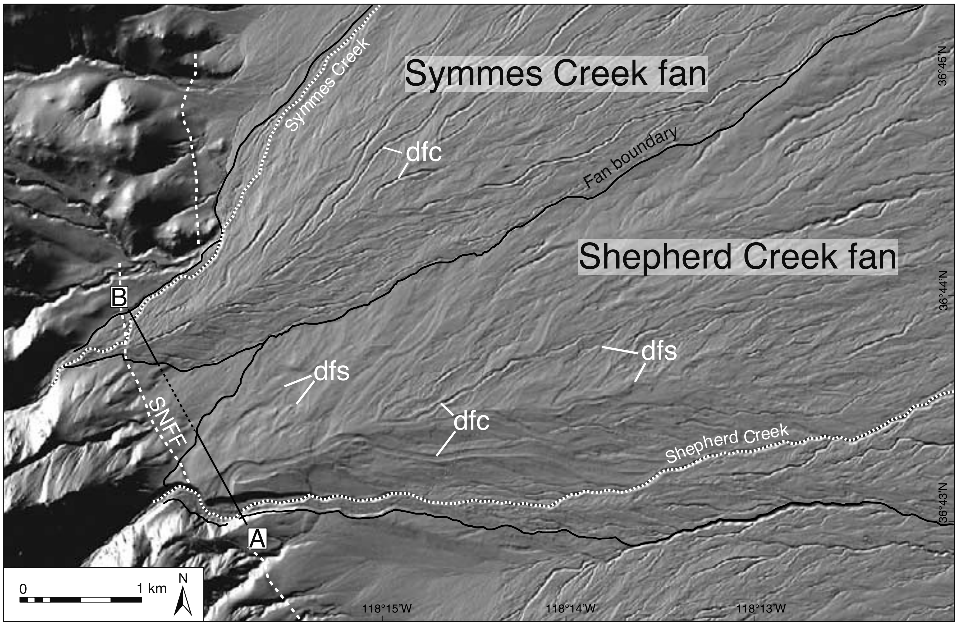

Figure 2. Shaded-relief map of Shepherd and Symmes creek fans showing the textural fan surface characteristics. Topography is derived from airborne laser swath mapping (ALSM) topographic data with resolution of 1 m/pixel. Line A–B indicates the location of the topographic profile shown in Figure 3. The fan boundaries are outlined by solid black lines; the active channels are shown by dotted white lines. Boundaries of the figure correspond with margins of the ALSM data and do not include all of the distal fan areas. SNFF, Sierra Nevada frontal fault. Examples of former debris flow channels and snouts are labeled as dfc and dfs, respectively.

Creek and 2230 m for Symmes Creek. The catchments are underlain by a series of Mesozoic granite, granodiorite and monzonite plutons [*Moore*, 1963, 1981]. Today, the dominant sediment transport processes in both catchments are inferred to be bedrock landsliding, debris flows, and fluvial transport and incision.

[9] Both fan catchments are unglaciated today, but they were affected by different degrees of glaciation during the late Pleistocene [*Brocklehurst and Whipple*, 2002]. Longitudinal valley profiles show that while Shepherd Creek catchment was significantly modified by glacial erosion, Symmes Creek catchment shows no apparent sign of glacial modification [*Brocklehurst and Whipple*, 2002]. From this, we infer that glacial occupation was significant in Shepherd Creek and minor (D. H. Clark, personal communication, 2006) in Symmes Creek catchment.

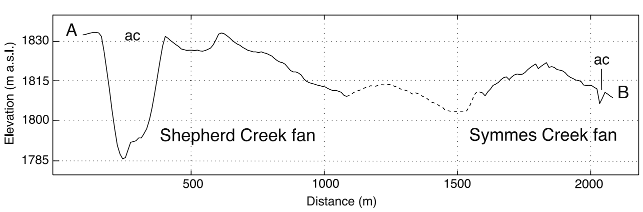

Figure 3. Topographic profile across the proximal Shepherd and Symmes creek fans. Topographic data were extracted from 1 m-resolution airborne laser swath mapping data. For the profile locations A–B, see Figure 2. The letters ac stand for active channel. Dashed segment indicates a fan cone from a small catchment between Shepherd and Symmes creeks. Note the incision of the Shepherd Creek fan head by about 45 m; in contrast, incision of the Symmes Creek fan head is less than 5 m.

[10] Today, the climate of the eastern Sierra Nevada is mainly influenced by the westerly polar jet stream, which brings precipitation from Pacific cyclones to this area. Another source of precipitation occurs during the summer when monsoonal storms from the Pacific and the Gulfs of California and Mexico carry tropical moisture into Owens Valley [*Hales*, 1974]. In total, the mean annual precipitation on the Owens Valley floor is about 100–150 mm yr^{-1} and increases to more than 750 mm yr^{-1} at the range crest of the Sierra Nevada [*Hollet et al.*, 1991].

[11] In summary, our study catchments have experienced similar tectonic displacement rates, base level conditions, and large-scale climatic forcing during the late Quaternary. They differ largely in the degree of glaciation within the catchments and in the presence or absence of fan head incision. We now examine the effects of these factors on the geomorphology of the fan surfaces and the patterns of exposure ages.

3. Debris Flow Fans

[12] Debris flow fans are different from fluvial fans in both the processes of sediment transport and deposition, and the resulting surface morphology. Granular debris flows, such as those from the granitic catchments of the eastern Sierra Nevada, leave behind a typically linear sediment deposit consisting of a fairly straight, shallow channel, lateral levees that are relatively coarse grained compared to the body of the flow, and a coarse-grained snout (Figures 2

Figure 4. Field photos of debris flow channels and snouts. Dashed lines indicate levees and snouts, and arrows show the flow direction. Note circles with person for scale. (a) Debris flow channel on Shepherd Creek fan. View is to the east. Channel width is about 40 m, and the mean boulder size is 1 m. (b) Debris flow channel on Symmes Creek fan. View is to the west. Channel width is about 25 m, and the mean boulder diameter is 2 m. (c) Debris flow snouts with equal runout distance indicating contact between lobes A and B on Shepherd Creek fan. View is to the south.

and 4). Since deposition during a single debris flow is generally restricted to one or a few channel-levee complexes, the region of active deposition must shift laterally over time in order to resurface the whole fan [*Dutton*, 1880]. Short-term shifts in the depocenter can occur abruptly because of channel blockage and avulsion during individual flow events [*Beaty*, 1963; *Hooke*, 1967; *Whipple and Dunne*, 1992], and may be superimposed on a longer-term lateral or radial switching between different regions of the fan, producing distinct fan segments or lobes, driven by changes in climatic, tectonic or base-level conditions. Areas of a fan that are low relative to surrounding regions are particularly prone to avulsion and reoccupation by a new fan lobe. These shifts in deposition cause abandonment of the active depocenter and lead to deposition on, and resurfacing of, formerly inactive fan areas.

4. Methods

4.1. Relative Fan Lobe Chronology

[13] We mapped distinct fan lobes on Shepherd and Symmes creek fans using a variety of criteria, including (1) surface morphology and preservation of debris flow deposits, (2) short-wavelength (1–10 m) surface relief, (3) boulder diameter, (4) degree of boulder weathering, (5) channel width, and (6) debris flow levee height. In the field, we measured the diameter of at least 200 boulders per lobe, while the height of well-preserved levees was measured with a differential GPS at $\sim$1 cm precision in 5–10 places per lobe. Surface roughness and degree of boulder weathering were assessed qualitatively. Levee height was also estimated, along with channel width between levee crests, on digital airborne laser swath mapping (ALSM) topographic data with a spatial resolution of 1 m/pixel and a vertical accuracy of 5–10 cm (Figure 2). Height and width estimates were made approximately every 100 m along well-preserved debris flow channels. Results from the ALSM data agree to <0.5 m with our more limited field measurements of levee height.

[14] We established the relative timing of different fan lobes using crosscutting relationships between debris flow channels and differences in relative elevation. Contacts between adjacent lobes were defined on the basis of (1) abrupt lateral changes in surface morphology that could be traced for tens to hundreds of meters, and (2) downlapping debris flow deposits that define clear boundaries between topographically distinct areas of the fan surface [e.g., *Blair*, 1999]. Because the subdued relief on the distal fans makes it difficult to map age relationships with confidence, we limited our work to a radial length of about 5 km from both catchment mouths.

4.2. Absolute Fan Surface Ages

[15] Using the relative fan surface chronology as a framework, we dated fan lobes using the in situ produced cosmogenic radionuclide ^{10}Be. We sampled 32 granitic or granodioritic boulders on different lobes to get a representative distribution of surface exposure ages over the upper parts of both fans (Figure 5). Wherever possible, we took samples from recognizable debris flow channel levees and snouts, since these incorporate the largest boulders and are unlikely to have been moved or reworked by other processes after deposition. We assume that measured ages give a primary depositional age so that surface activity on each lobe occurred at least during the age range of our samples, and that lobe abandonment happened sometime after the

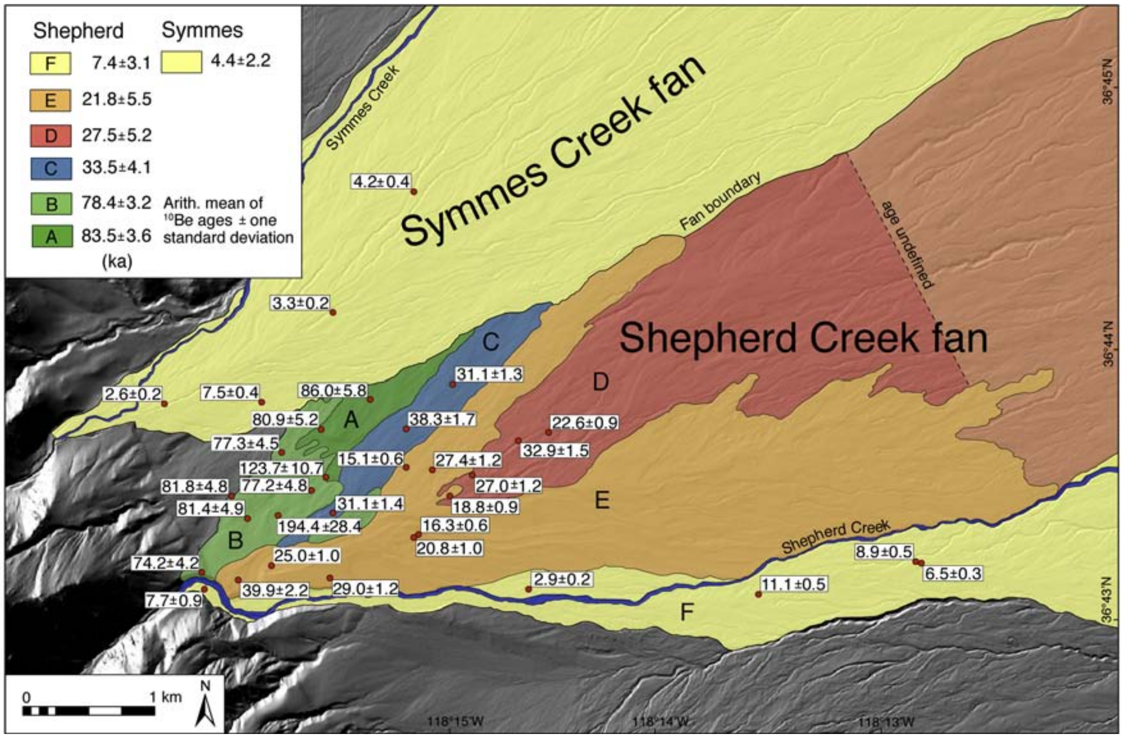

Figure 5. Relative and absolute chronologies of fan deposition on Symmes and Shepherd creek fans. Colored lobes (Symmes and Shepherd A–F) represent the relative chronology based on mapping of debris flow deposits with similar geomorphic signatures and crosscutting relationships between channels. Red points indicate sample locations for cosmogenic ^{10}Be surface exposure dating. See Tables 1 and 2 for sample details. Inset shows arithmetic mean of sample ages on each fan lobe (see also Table 2). Note good agreement between absolute and relative chronology. The Shepherd Creek fan surface preserves a longer record of fan deposition due to fan head incision and lobe abandonment. In contrast, Symmes Creek fan has been completely resurfaced in the Holocene.

youngest age on a lobe. Thus our ages provide a maximum age for each lobe, and a minimum duration for deposition on that part of the fan.

[16] We only sampled boulders larger than 1 m in diameter and standing more than 1 m above the fan surface, and took 3–5 cm thick flakes from flat-topped upper boulder surfaces. We preferred collecting boulders that were slightly varnished and covered by lichens and avoided boulders with obvious signs of recent erosion (e.g., spalling or fracturing) of the surface. On fan lobes with few appropriate sampling sites because of insufficient boulder size or apparent boulder erosion, we collected fewer samples (a minimum of three per lobe). Consequently, the number of samples per lobe is not evenly distributed.

[17] Our use of boulder exposure ages to constrain the timing of debris flow deposition is potentially complicated by two factors: inherited ^{10}Be due to significant prior exposure before deposition, and reworking of older boulders in later debris flows. To test for an inherited ^{10}Be signal, we sampled boulders from debris flow levees on lobe F (Figure 5) along the active channel of Shepherd Creek. Assuming that these deposits represent the most recent debris flow events on the Shepherd Creek fan, these boulders should yield very young ages (on the order of a few ka) if inheritance is minimal, implying that residence times in the catchment are short. While this approach allows us only to quantify the present degree of inheritance, it seems plausible that inheritance during past glacial epochs should be even lower, given the likelihood of higher erosion rates and sediment discharge during those times (D. H. Clark, personal communication, 2006). Major reworking of older boulders should be visible as a wide spread of ages on a single depositional lobe and overlapping boulder ages between lobes. To minimize the chances of sampling reworked boulders, we limited our sampling to boulders whose appearance was representative for each lobe, and avoided boulders with greater degrees of surface weathering or desert varnish than the majority. While this sampling approach may introduce a slight bias toward younger exposure ages, the effect is unlikely to be important because the proportion of "older-looking" boulders on each lobe was less than 5%.

[18] We separated quartz from the boulder samples and extracted Be using standard techniques according to *Kohl and Nishiizumi* [1992], *Ivy-Ochs* [1996], and *Ochs and Ivy-Ochs* [1997]. The isotopic ratios were determined by accelerator mass spectrometry (AMS) at ETH Zürich. We ran nine process blanks altogether and used their weighted mean ratio of $2.54 \times 10^{-14} \pm 2.12 \times 10^{-15}$ for the correction of the measured isotopic samples. Exposure ages were calculated on the basis of the model of *Lal* [1991]:

$$N = \frac{P}{\lambda + \frac{\rho\varepsilon}{\Lambda}}\left[1 - e^{-\left(\lambda + \frac{\rho\varepsilon}{\Lambda}\right)T}\right] \quad (1)$$

Table 1. Boulder Information: Elevation, Sampling Location, and Surrounding Topography Corrections

Boulder Number	GPS Elevation, m	Latitude, deg N	Longitude, deg W	Shielding Correction[a]
Symmes Creek Fan				
MD270303_1	1695	36.735	118.257	0.999
MD200404_1	1848	36.730	118.271	0.999
MD250305_1	1642	36.743	118.252	0.992
MD200404_6	1779	36.730	118.264	0.994
Shepherd Creek Fan				
Lobe A				
MD250303_1	1700	36.731	118.256	0.998
MD210404_5	1763	36.728	118.259	0.996
MD190305_1	1782	36.725	118.259	0.991
Lobe B				
MD200404_3	1898	36.719	118.268	0.995
MD170305_1	1826	36.724	118.266	0.991
MD170305_3	1837	36.723	118.265	0.990
MD170305_5	1793	36.724	118.260	0.991
MD230305_3	1819	36.723	118.262	0.990
MD170305_2	1788	36.727	118.262	0.994
Lobe C				
MD170305_6	1793	36.723	118.258	0.991
MD190305_7	1722	36.728	118.253	0.994
MD190305_6	1681	36.731	118.249	0.992
Lobe D				
MD150305_4	1657	36.728	118.242	0.994
MD150305_2	1672	36.728	118.244	0.995
MD150305_5	1607	36.726	118.248	0.994
Lobe E				
MD200404_4	1862	36.719	118.265	0.993
MD210404_4	1743	36.722	118.252	0.994
MD210404_3	1743	36.722	118.252	0.994
MD170305_4	1845	36.720	118.263	0.992
MD180305_4	1730	36.726	118.251	0.994
MD230305_5	1745	36.726	118.253	0.994
MD160305_1	1801	36.719	118.258	0.991
MD240305_9	1728	36.724	118.249	0.995
Lobe F				
MD210404_1	1448	36.720	118.213	0.999
MD210404_2	1492	36.721	118.214	0.999
MD180305_2	1570	36.718	118.226	0.996
MD160305_3	1682	36.719	118.243	0.994
MD240305_1	1871	36.718	118.268	0.981

[a]Shielding correction includes shielding of surrounding topography but does not include snow or erosion corrections.

where N is the measured nuclide concentration, P the production rate, λ the decay constant of ^{10}Be (4.59×10^{-7} yr^{-1}), ρ the density of the sample rock (2.7 g cm^{-3}), ε the erosion rate on the boulder surface, Λ the cosmic ray attenuation length in the rock surface (165 g cm^{-2}), and T is the time.

[19] For the calculation of ^{10}Be we used a production rate of 5.1 ± 0.3 atoms g^{-1} SiO_2 yr^{-1} after *Stone* [2000]. The production rates for ^{10}Be were scaled for latitude and elevation after *Stone* [2000] and corrected for topographic shielding and sample thickness (Table 1). The exposure ages listed in Table 1 have not been corrected for past variations in the Earth's magnetic field. On the basis of the model of *Masarik et al.* [2001] this correction at this site would be 4% or less. In contrast, on the basis of the model of *Pigati and Lifton* [2004], samples with ages ranging between 160 and 70 ka would have exposure ages that are ~11% younger. For those with ages between 15 and 40 ka this effect varies between −4 to +7%. Holocene ages would be 10 to 18% older. Until a better consensus exists on the method of correcting, we do not make these corrections. We note that changes in the ages of these magnitudes would have little bearing on the conclusions made here.

[20] To correct the exposure ages for the effect of boulder surface weathering, we have assumed an erosion rate of 2 ± 0.5 mm ka^{-1}. This is a reasonable rate for this area, climatic setting, and rock type [*Small et al.*, 1997; *Zehfuss et al.*, 2001]. We use the assumed value, rather than a maximum erosion rate calculated by using the nuclide concentration in our oldest boulder, because we have no way of knowing if our sample has achieved steady state concentrations of ^{10}Be, and there is no reason to believe that we sampled the oldest boulder on the fan. The error on each boulder age includes the quadratic sum of the analytic uncertainty and the error on the erosion rate. The averaged exposure age for each fan lobe is the arithmetic mean of boulder ages on that lobe ± one standard deviation.

5. Results

5.1. Relative Fan Lobe Chronology and Surface Morphology

[21] The surface of Symmes Creek fan comprises a single depositional lobe with nearly uniform surface characteristics (Figure 5). The debris flow channels are about 20–30 m wide and 2–3 m deep. Debris flow levees are well defined along nearly all channels and are composed of mostly fresh, unweathered boulders with a maximum diameter of up to 8 m. Debris flow snouts are common and are often nested within channels, showing repeated occupation of channels and progressive upstream deposition in successive surges or flows [*Whipple and Dunne*, 1992]. Areas between channels are mantled by grus. The active channel at the head of Symmes Creek fan is incised by less than 5 m into the fan surface (Figure 3), and this incision depth is relatively invariant downfan.

[22] In contrast, the surface of Shepherd Creek fan can be divided in the field into six different depositional lobes, named A to F in order of decreasing age (Figure 5). Lobes A–E are preserved above the modern, active lobe F thanks to incision of the fan head by Shepherd Creek (Figure 3). This incision decreases downfan from 45 m at the fan head to a few meters at a distance of 1.5 km from the head, and is invariant below this point.

[23] Lobe A is the oldest fan lobe and has a very smooth surface, largely mantled by grus. No clearly recognizable debris flow channels are preserved, and therefore no measurements of channel width or levee height were made. Local concentrations of large boulders may represent former debris flow levees and snouts, although their geometry is difficult to reconstruct. The boulders have diameters between 1 and 3 m, the largest up to 5 m. Some of these boulders are covered by desert varnish and show no apparent sign of erosion. Others have a fractured surface with clearly recognizable areas of surface erosion.

[24] The next-youngest lobe B has clearly visible, radially oriented ridges and channels. These probably represent relict debris flow channels, but smoothing of the surface makes it difficult to measure the original channel geometries. Boulders on this lobe are similar in their surface characteristics to boulders on lobe A, but are smaller on

average, with diameters of 1–2 m. The abrupt eastern, downfan margin of lobe B is formed by a north–south oriented line of pronounced debris flow snouts that downlap onto the topographically lower lobe A (Figure 4). These snouts show that the transition from deposition on lobe A to lobe B was accompanied by a change to shorter debris flow runout lengths, leading to a headward shift in the active depocenter on the fan.

[25] Lobe C is small in area and, like A, has a smooth, grus-mantled surface without a recognizable channel-levee morphology. Instead sedimentation has occurred in thin (<0.5 m), clast-rich lobate deposits. These deposits are elongate downfan, have relatively consistent widths of about 15 m, and end in subdued, coarser-grained snouts. The boundaries between the flow deposits and the intervening, clast-free and grus-mantled fan surface are very sharp. Cobbles and boulders are very abundant in the lobate deposits, but the boulders are significantly smaller than those on lobes A and B, with a mean diameter of less than 1 m and very rare clasts to 3 m. In general, the boulders are unvarnished and relatively unweathered compared to those on lobes A and B. During deposition on this surface, channels appear to have either incised through deposits of lobe B or reactivated an older channel on lobe B to reach their present locations.

[26] After abandonment of lobe C, the style of deposition shifted to channelized, leveed debris flow deposits on lobe D (Figure 5). Short-wavelength relief on this surface is generally 3–5 m because of prominent, well-developed debris flow channels and levees. Channels are 25 to 35 m wide and about 1–2 m deep. The levees are composed of unweathered, mostly unvarnished boulders of intermediate size (1–2 m). In comparison with lobes C and E, this lobe has significantly more boulders deposited along its levees, and well-preserved boulder-rich snouts are much more frequent.

[27] The channels on lobe D are crosscut and partially mantled by the widespread deposits of lobe E, which covers at least one third of the proximal fan area (Figure 5). There are few debris flow channels on this lobe, but those that exist have widths of 50–60 m and depths of 2–3 m. Boulders on this lobe are rare and have generally diameters of less than ~0.5 m. The most pronounced channel on this lobe has a maximum width of 100 m and extends a distance of about 3 to 4 km from the fan head (Figure 5). Small patches of older deposits, correlative with those on lobe C, that are found near the head of this channel suggest that it originally formed during activity on lobe C, and was reoccupied by debris flows during deposition of lobe E. These patches also show that younger lobes may not completely cover older deposits, leaving "windows" that expose older flows. This can potentially complicate our interpretations of surface morphology and exposure ages. Abandonment of lobe E coincided with the major incision of the fan head that characterizes the present-day Shepherd Creek fan.

[28] The presently active lobe F consists of inset terraces and the floor of the incised channel at the head of Shepherd Creek fan, and the laterally equivalent depositional area downfan (Figure 5). Debris flow channels are 15 to 25 m wide and less than 2 m deep. In comparison to other lobes on Shepherd Creek fan, this surface is characterized by a very high abundance of boulders with a mean diameter of 1–2 m. These boulders are unweathered, show little to no desert varnish, and form sharply defined levees and snouts as well as random boulder fields. Snouts are often nested or superimposed on each other within a single channel because of deposition in successive surges or debris flows. Of all the lobes on the Shepherd Creek fan, lobe F is most similar to the surface of Symmes Creek fan in terms of its morphology. The most prominent difference between the surfaces is the depth of the debris flow channels, which is consistently larger on the Symmes Creek fan.

5.2. Fan Depositional Ages From Cosmogenic Radionuclides

[29] Surface exposure ages were determined for 32 boulders on the two fans (Table 2). If we assume no inheritance and a postdepositional boulder erosion rate of 2 ± 0.5 mm ka^{-1}, our ^{10}Be data yield ages of 7.5 ± 0.4 to 2.6 ± 0.2 ka on Symmes Creek fan, and 194.4 ± 28.4 to 2.9 ± 0.2 ka on Shepherd Creek fan (Table 2 and Figure 5).

[30] All four Symmes Creek fan samples yield Holocene ages, consistent with our observations that the fan surface is relatively uniform and shows excellent preservation of primary debris flow deposits. The small number of samples means that we are unable to determine if the surface of Symmes Creek fan records intra-Holocene variations in deposition, as inferred, for example, by *Wells et al.* [1987] for fans in the Mojave Desert. In addition, the low nuclide concentrations of the Symmes Creek fan samples, as well as those from the active lobe F on Shepherd Creek fan (Table 2 and Figure 5), show that inherited ^{10}Be due to prior exposure in the catchment is relatively unimportant at present, and that boulders were exposed for at most a few thousand years (comparable to the uncertainty on our many of our exposure ages, and in agreement with the ≤2.0 ka inheritance inferred by *Bierman et al.* [1995]) before being transported onto the fan surface. Thus we infer that the boulder exposure ages effectively date the time of debris flow deposition.

[31] On Shepherd Creek fan, the oldest surface (lobe A) yields ages of 123.7 ± 10.6, 86.0 ± 5.8, and 80.9 ± 5.2 ka. Six of the seven samples on lobe B are indistinguishable within error from the latter two ages, varying between 81.8 ± 4.8 and 74.2 ± 4.2 ka. Thus the apparent transition from lobe A to lobe B may simply reflect the surface preservation of later flows closer to the fan apex on a single depositional lobe. It is possible that the seventh age on lobe B, 194.4 ± 28.4 ka, and the older age of 123.7 ± 10.6 ka on lobe A, are not representative of the true depositional age of this lobe. This result could be explained by high nuclide inheritance of the two measured boulders, or it could be that they occur in "windows" that expose an older, underlying fan lobe. On the basis of our limited sampling, we cannot distinguish between these possibilities, but we consider the first more unlikely.

[32] There is a gap of about 30 ka between the ages on lobe B and the oldest depositional age on lobe C. Two samples collected from separate debris flow levees on lobe C yield ages of 31.1 ± 1.4 and 31.1 ± 1.3 ka, while a snout on lobe C yields an age of 38.3 ± 1.7 ka. These ages partially overlap, within error, the oldest ages on lobe D, which are between 32.9 ± 1.5 and 22.6 ± 0.9 ka. Recall that

Table 2. AMS-Measured ^{10}Be Concentration and Calculated Exposure Ages

Boulder Number	^{10}Be,[a] 10^5 atom g^{-1}	^{10}Be Model Age, ka[b]	^{10}Be Model Age + 2 mm ka^{-1} Erosion, ka[c]
Symmes Creek Fan			
MD270303_1	0.55 ± 0.05	3.3 ± 0.2	3.3 ± 0.2 (0.3)
MD200404_1	0.48 ± 0.03	2.6 ± 0.2	2.6 ± 0.2 (0.2)
MD250305_1	0.68 ± 0.06	4.2 ± 0.4	4.2 ± 0.4 (0.4)
MD200404_6	1.31 ± 0.07	7.4 ± 0.4	7.5 ± 0.4 (0.6)
Mean age of lobe[d]		4.4 ± 2.1	4.4 ± 2.2
Shepherd Creek Fan			
Lobe A			
MD250303_1	12.83 ± 0.51	74.5 ± 3.0	86.0 ± 5.8 (7.7)
MD210404_5	12.47 ± 0.49	70.7 ± 2.8	80.9 ± 5.2 (7.1)
MD190305_1[e]	17.80 ± 0.54	100.8 ± 3.0	123.7 ± 10.6 (12.9)
Mean age of lobe[d]		72.6 ± 2.7	83.5 ± 3.6
Lobe B			
MD200404_3	12.79 ± 0.39	65.5 ± 2.0	74.2 ± 4.2 (6.1)
MD170305_1	13.08 ± 0.40	71.4 ± 2.1	81.8 ± 4.8 (6.9)
MD170305_3	13.11 ± 0.41	71.1 ± 2.2	81.4 ± 4.9 (6.9)
MD170305_5	12.17 ± 0.48	67.9 ± 2.6	77.2 ± 4.8 (6.6)
MD230305_3[e]	25.37 ± 0.77	141.5 ± 4.2	194.4 ± 28.4 (30.7)
MD170305_2	12.37 ± 0.38	67.9 ± 2.0	77.3 ± 4.5 (6.4)
Mean age of lobe[d]		68.8 ± 2.4	78.4 ± 3.2
Lobe C			
MD170305_6	5.34 ± 0.19	29.8 ± 1.1	31.1 ± 1.3 (2.3)
MD190305_7	6.18 ± 0.22	36.2 ± 1.3	38.3 ± 1.7 (2.9)
MD190305_6	4.94 ± 0.19	29.8 ± 1.1	31.1 ± 1.4 (2.3)
Mean age of lobe[d]		31.6 ± 3.7	33.5 ± 4.1
Lobe D			
MD150305_4	3.88 ± 0.14	21.9 ± 0.8	22.6 ± 0.9 (1.6)
MD150305_2	5.19 ± 0.20	31.4 ± 1.2	32.9 ± 1.5 (2.5)
MD150305_5	4.37 ± 0.17	26.0 ± 1.0	27.0 ± 1.2 (2.0)
Mean age of lobe[d]		26.2 ± 4.7	27.5 ± 5.2
Lobe E			
MD200404_4[e]	7.08 ± 0.33	37.7 ± 1.8	39.9 ± 2.2 (3.2)
MD210404_4	3.53 ± 0.15	20.3 ± 0.8	20.8 ± 1.0 (1.6)
MD210404_3	2.78 ± 0.09	16.0 ± 0.5	16.3 ± 0.6 (1.1)
MD170305_4	4.50 ± 0.16	24.2 ± 0.8	25.0 ± 1.0 (1.8)
MD180305_4	4.54 ± 0.18	26.4 ± 1.0	27.4 ± 1.2 (2.1)
MD230305_5	2.59 ± 0.10	14.8 ± 0.5	15.1 ± 0.6 (1.1)
MD160305_1	5.03 ± 0.18	27.9 ± 1.0	29.0 ± 1.2 (2.1)
MD240305_9	3.16 ± 0.15	18.4 ± 0.9	18.8 ± 0.9 (1.5)
Mean age of lobe[d]		21.0 ± 5.1	21.8 ± 5.5
Lobe F			
MD210404_1	1.24 ± 0.06	8.8 ± 0.5	8.9 ± 0.5 (0.7)
MD210404_2	0.94 ± 0.05	6.5 ± 0.3	6.5 ± 0.3 (0.5)
MD180305_2	1.67 ± 0.08	10.9 ± 0.5	11.1 ± 0.5 (0.8)
MD160305_3	0.48 ± 0.04	2.9 ± 0.2	2.9 ± 0.2 (0.3)
MD240305_1	1.42 ± 0.07	7.6 ± 0.3	7.7 ± 0.3 (0.6)
Mean age of lobe[d]		7.3 ± 3.0	7.4 ± 3.1

[a]For blanks, n = 9. Errors on measured atoms are based on AMS uncertainty, including the statistical counting error and the error due to the normalization to the standards and the blank.

[b]Errors on individual ^{10}Be ages assuming zero erosion reflect analytic uncertainty including AMS error and corrections for elevation, latitude, shielding, and sample thickness.

[c]Erosion-corrected ^{10}Be exposure ages assuming an erosion rate of 2 ± 0.5 mm ka^{-1}. Errors on each sample include analytic uncertainty and the error on the erosion rate. In parentheses are errors which also include systematic uncertainty of the production rate [*Stone*, 2000].

[d]Ages on a single lobe represent the arithmetic mean of sample ages ± one sigma standard deviation.

[e]Sample ages are excluded from the calculation of arithmetic mean age of a single fan lobe.

lobes C and D are distinguished by their very different surface characteristics in the field – thin lobate deposits on lobe C, and boulder-rich debris flow levee-channel complexes on lobe D. On the basis of our sampling, we cannot determine whether lobe C formed before deposition shifted to lobe D, or whether it represents a distinct episode, early in the deposition of lobe D, of unchannelized flows that were relatively poor in large boulders.

[33] Exposure ages on lobe E range from 39.9 ± 2.2 ka to 15.1 ± 0.6 ka (Figure 5). Again, there is some overlap of the older ages with those of the previously active fan lobe, despite clear and spatially distinct differences in surface morphology between lobes. The oldest boulder age of 39.9 ± 2.2 ka likely represents a "window" exposing older fan sediments, as it occurs within a channel that appears to have been active during the formation of lobe C and later reoccupied during deposition of lobes D and E. Therefore it is possible that this boulder was originally deposited during activity on lobe C. The remaining seven ages on lobe E are <29 ka, and three are <20 ka.

[34] The final event recorded by our exposure ages on Shepherd Creek fan is the incision of the fan head and abandonment of lobe E. This must have occurred sometime after the youngest age on lobe E, 15.1 ± 0.6 ka. As incision progressed, the depocenter shifted basinward to establish lobe F, which yields ages of 11.1 ± 0.5 to 2.9 ± 0.2 ka. Four out of five sampled boulders on this lobe have ages ranging between 11.1 ± 0.5 and 6.5 ± 0.3 ka, which may suggest a focus of depositional ages during the early to middle Holocene.

6. Discussion

[35] In summary, the presence or absence of fan head incision leads to strikingly different fan surface characteristics and patterns of exposure ages. The surface of Symmes Creek fan is morphologically almost uniform and appears to have undergone widespread resurfacing in the Holocene on the basis of four ^{10}Be exposure ages. In contrast, incision of the Shepherd Creek fan head has led to the preservation of at least five, and probably six, geomorphically distinct lobes. The contacts between the lobes can be clearly defined, and key surface characteristics such as boulder diameter, surface roughness, development of debris flow levees, and channel geometry, vary between lobes. Boulder exposure ages on Shepherd Creek fan are generally internally consistent on individual lobes (Figure 6), with the exception of single older ages on Shepherd Creek lobes A, B, and E. While our samples provide only minimum estimates for the lifespan of each lobe, individual lobes appear to have remained active for periods of about 5–15 ka, and in most cases were abandoned without any evidence of depositional hiatus. Successive, geomorphically distinct lobes have exposure ages that are progressively younger but generally overlap somewhat with adjacent lobes. For the moment, we do not know whether this overlap is a function of age uncertainty (partly because of boulder inheritance), exposure of older deposits through surface "windows," or real variability in the locus of debris flow deposition. The surface relations on lobes A and B are consistent either with a shift to shorter runout distances during deposition of lobe B, or preservation of only the later flows at the fan head during deposition of a single lobe. Taken alone, the overlapping exposure ages could be interpreted as indicating as few as 3 distinct lobes- A–B, C–E, and F. Such an interpretation would, however, ignore the sharp geomorphic differences between lobes, and would require an independent explanation for why spatially con-

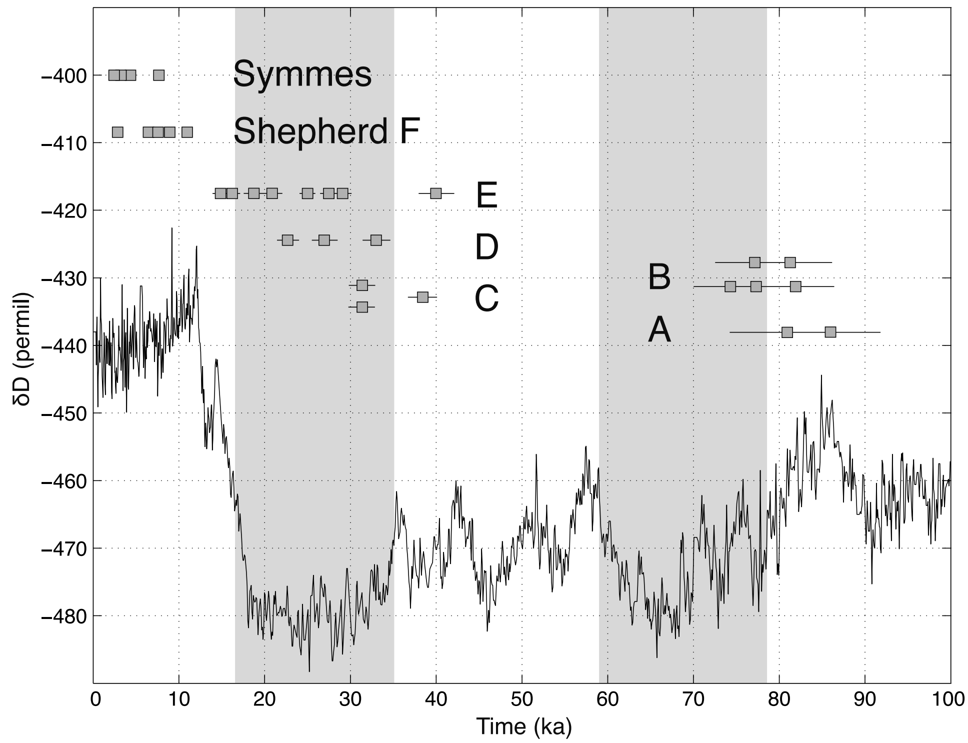

Figure 6. Distribution of cosmogenic ^{10}Be boulder ages on Shepherd and Symmes creek fans plotted against the Vostok δD record of *Petit et al.* [1999]. Error bars on the ages include analytical uncertainty and systematic errors in the production rate. Samples MD190305_1 and MD230305_3 (Table 2) are excluded from this plot because of their old ages. Labels A–F refer to fan lobes on Shepherd Creek fan. Timing and duration of marine isotope stages 2 and 4 based on the Vostok curve are indicated by gray boxes. These periods correlate with major glacial advances in the Sierra Nevada. The distribution of ages suggests that debris flow deposition occurs during both glacial and interglacial periods but may be particularly enhanced during glacials [*Bierman et al.*, 1991, 1995].

tiguous portions of the fan have such distinct surface morphologies. We argue therefore that lobes A–F, given the uncertainty in our exposure ages, mark progressive shifts in the active fan surface through time. Our results emphasize that exposure age dating must be combined with careful, independent field work in order to understand the evolution of fan surfaces.

[36] Our ages show that debris flow deposition on Owens Valley fans occurs during both glacial and interglacial times (Figure 6), as noted by *Bierman et al.* [1995] for the Lone Pine fan. The spatially limited extent of the Holocene lobe F on Shepherd Creek fan, the large MIS 2 lobes D and E, and the relative paucity of interglacial exposures ages (Figure 6) also lead us to concur with *Bierman et al.* [1995] that the Holocene debris flow deposition rate, and thus the Holocene sediment efflux from the Shepherd Creek catchment, is likely to be lower than that of the Pleistocene. Note that this inference is not necessarily incompatible with the Holocene resurfacing of the Symmes Creek fan. Given the voluminous and areally extensive Pleistocene deposits on other fans in Owens Valley [*Bierman et al.*, 1995; *Zehfuss et al.*, 2001], it seems likely that similarly aged deposits are present on Symmes Creek fan but are simply buried by widespread Holocene deposits, and the lack of fan head incision has prevented preservation of older lobes. The specific reasons for this Holocene decrease in debris flow deposition must remain speculative [*Bierman et al.*, 1991]. While it is well established that glacial climates in the southwestern United States in general, and the Sierra Nevada in particular, were cooler and significantly wetter than today [e.g., *Benson and Thompson*, 1987; *Benson et al.*, 1990; *Thompson et al.*, 1993; *Hostetler and Clark*, 1997; *Menking et al.*, 2004; *Li et al.*, 2004; *Robert*, 2004; *Stock*, 2004; *Kessler et al.*, 2006], the direct link between climatic conditions and increased rates of either debris flow occurrence or sediment transport are not yet clear and remain a primary research objective.

[37] More generally, our results point out the possible variations in surface depositional chronology between adjacent fans with similar tectonic and base level histories and comparable climatic conditions, and we thus suggest that caution must be used when inferring paleoenvironmental variables from single fan surface records. We identify at least two sources of this variation. The most obvious is due to the role of fan head incision in preserving or burying older fan deposits. Comparison of exposure ages from Shepherd Creek fan and other nearby fans with incised heads in Owens Valley, however, also reveals some important differences. The oldest exposed lobes on the well-dated, incised Lone Pine and Fish Springs fans yield multiple exposure ages in excess of 100 ka [*Bierman et al.*, 1995; *Zehfuss et al.*, 2001]; in contrast, only two of our samples are as old, and both appear to be outliers on somewhat younger depositional surfaces. Thus the Lone Pine and Fish

Springs fans, despite comparable present-day amounts of fan head incision as the Shepherd Creek fan [*Dühnforth*, 2007, chapter 4], preserve surface evidence of an older depositional episode not recorded by the Shepherd Creek fan. Conversely, we find evidence for deposition on lobes A and B between 74 and 86 ka (Figure 6), an age range that is not found on the Lone Pine or Fish Springs fans. We suggest that these apparent discrepancies are most likely due to the vagaries of lobe preservation and abandonment on debris flow fans. Given that older lobes may be rapidly buried and obscured by younger deposits following an avulsion, and given that avulsions are likely to be somewhat stochastic in space and time, it seems unlikely that all fans in a given area will preserve the same surface record of fan deposition, even without factoring in variables like fan head incision.

[38] A final issue that is raised by our data is the effect of fan head incision on the stratigraphic record of fan deposition. A seemingly obvious, but perhaps not widely appreciated, corollary of fan lobe switching is that the abandonment of large parts of the fan surface introduces local unconformities into the fan stratigraphy. Solely on the basis of present-day exposure ages from Owens Valley fans, these unconformities may cover much of the fan surface and represent missing time intervals of at least 100 ka. Note also that unconformities are not limited to distal portions of the fan surface; the oldest exposed portions of the Shepherd Creek fan occur in the proximal fan area, and would represent the largest time gaps if those portions were to be resurfaced. Thus a single section through an incised, Shepherd-type fan at any one place may record only a fraction of the total depositional history, when in fact deposition on the fan as a whole may be quasi-continuous (and may be better recorded by adjacent, unincised fans like Symmes Creek). Particularly in arid regions, such unconformities will be difficult to spot in the absence of significant soil development between debris flow deposits or without sufficient datable material.

[39] Thus, for all their potential utility, fan surfaces may not necessarily reveal a complete record of sediment supply from their associated catchments. Depending on the presence or absence of fan head incision and the fan-specific history of avulsion events, a single fan surface will provide at best a portion of the true depositional history. Broad regional correlations between sediment supply, fan deposition, and external driving forces, such as climatic conditions or tectonic displacement, should thus ideally be based on multiple fan surface records.

7. Conclusions

[40] The presence or absence of fan head incision is a first-order control on the spatial patterns of debris flow deposition and the length of the preserved surface chronologies on Shepherd and Symmes creek fans. The incised Shepherd Creek fan surface consists of multiple depositional lobes, which are geomorphically distinct and appear to have been active and abandoned at different times. Cosmogenic ^{10}Be exposure ages are progressively younger on more recently active fan lobes, but commonly overlap with ages on adjacent lobes. This overlap may be a function of uncertainty on the exposure ages, or it may represent real variability in the locus of debris flow deposition with time. Lobes were active for periods of $\sim$5–15 ka before being abandoned by lateral or radial shifts in the fan depocenter. Major debris flow deposition occurred during the late Pleistocene glaciations of the Sierra Nevada, and to a somewhat lesser extent during the Holocene. In contrast, the unincised Symmes Creek fan is dominated by one major depositional lobe, which has resurfaced the entire fan during the Holocene. This complex variation in depositional timing between adjacent fans underscores the ability of fan head incision to preserve and isolate portions of the fan surface for periods of up to 100 ka, introducing potentially significant unconformities into the stratigraphic record on debris flow fans. In detail, the surface chronology recorded by Shepherd Creek fan differs from those of other incised fans in Owens Valley, most likely due to stochastic avulsion events on the fan surfaces that may obscure or bury older lobes. Our results suggest that attempts to link paleoenvironmental records with the timing of fan deposition, or to use fan surfaces as a proxy for tectonic or climatic conditions, should be done with caution unless multiple fan records are available for a region.

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